Economic Impacts of Debottlenecking Congestion in the Chinese Coal Supply Chain

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Key Points

- The extraordinary pace of development of China’s coal industry created transportation bottlenecks, which increased the price of delivered domestic coal and impacted global seaborne coal prices.
- Congestion costs added extra costs of energy supply to the Chinese economy, calculated to be RMB 228 billion in 2011.
- Debottlenecking has reduced the price of Chinese domestic coal delivered to the coastal regions and contributed to the reduction in global seaborne prices since 2011.
- Our analysis suggests that the existing tariff structure retains most of the economic efficiency of marginal cost pricing.
- Though many of the infrastructure expansions delivered strongly positive rates of return, some may represent pre-investment in future needs.

Executive Summary

China’s coal industry grew at unprecedented rates during the first decade of the 2000s in order to support equally unprecedented economic growth. In that type of environment, it is impossible for the capacities of every link in the supply chain to be correctly sized all the time. In order to understand the consequences of such mismatches, KAPSARC has developed a production and multi-modal transshipment model of China’s domestic coal market, calibrated to 2011 data. This allows us to examine what the global and domestic consequences might have been had the bottlenecks not existed in 2011.

Our analysis provides several key insights:

1. Debottlenecking the supply chain results in much lower domestic marginal costs for coal delivered to a coastal location, rendering thermal coal imports uneconomical. The resulting demand weighted average of marginal costs of thermal coal is some RMB 250 per ton less than the actual market price in 2011. These results support the view expressed by some analysts that the efforts made since 2011 to debottleneck China’s coal railway infrastructure have contributed to the recent decline in international coal prices.

2. Our estimate of the congestion costs incurred in 2011 is RMB 228 billion—experienced as a higher cost of coal delivered to consumers than would otherwise have been the case.

3. Building the infrastructure required to remove bottlenecks would have involved investing RMB 215 billion in rail capacity, well below the figures reported by analysts for planned and proposed coal rail projects during the past five years. This suggests either pre-investment that anticipates increases in post-2011 coal demand, or over-investment, as a form of economic stimulus or due to the inertia in large infrastructure investments.

4. Using a simple model based approach, we computed the economic returns on coal dedicated railway projects actually undertaken since 2011. They show a great disparity in their returns, with very high values for major corridors that our model identifies as attractive and low or negative values for others that the model did not require to debottleneck the system.

5. Optimizing the coal supply chain using the regulated transportation tariffs paid by users results in economic gains of RMB 223 billion. This amount is comparable with that achieved when optimizing on the basis of the actual economic costs of RMB 228 billion. Additionally, both perspectives result in similar marginal costs for the coal delivered. This shows that the existing tariff structure retains most of the economic efficiency of marginal cost pricing.

6. Improving the efficiency of the domestic transportation infrastructure without allowing reconfiguration of production results in slightly higher marginal costs of coal than were actually observed in 2011. Due to the improved
transportation infrastructure, more producers can implicitly arbitrage between selling coal locally and transporting it to a demand location where it could substitute for imports.

In the context of the model, this results in large economic rents for domestic coal producers since supply prices are higher while total cost is lower due to more efficient transportation. When production is allowed to respond to the expansion of transportation infrastructure to meet demand more efficiently, the economic rents fall, which results in much lower marginal costs of delivered coal.

We can conclude that expanding the domestic transportation infrastructure of a commodity at a speed that is different than adjustments in regional production capacities will result in temporary rents that disadvantage the end-consumer. The coordination gains—i.e. the elimination of these rents—quantify the value of adopting a systems view of the overall supply chain, and not focusing on only one piece at a time. By showing the possible price implications of expanding existing logistical infrastructure, a simple modeling approach like the one adopted here may assist policymakers to take a broader view of the consequences of investment and design policies or regulations that mitigate undesirable effects.

**Introduction to Chinese Coal Logistics**

China’s coal sector has developed rapidly, increasing annual production from 1.384 billion tons in 2000 to 3.516 billion tons in 2011 (National Bureau of Statistics 2013). Despite yearly investment surging from RMB 211 million in 2000 to RMB 5.4 billion in 2012 (NBS 2013), the domestic coal industry has faced a number of challenges, including the availability of coal resources, increasing production costs and constrained logistics. Transportation capacity, in particular, has been lagging behind the rapid supply expansion until recently. This led to transportation bottlenecks, primarily in the railway sector. The resulting congestion costs drove increases in the costs of delivered coal, because of the need to use trucks, and caused supply interruptions and price fluctuations.

The logistics of coal in China are determined by the locations of economic coal seams and the industrial and population centers where the coal is consumed. The growing supply sources are located primarily in the northern and western regions of China, while consumption takes place in the east. The provincial imbalances between coal production and consumption are shown in Figure 1. The exporting provinces are colored in shades of green and the importing provinces in shades of red. Transport expenses can account for up to 40 percent of total coal costs at the destination (Macquarie 2013), affecting producers’ competitiveness, capacity expansion and the overall performance of the industry. The major reason for the high cost of coal transportation was congestion costs resulting from the geographical mismatch between coal production and consumption.

Chinese coal reserves and production are mainly located in the western and northern inland provinces. The two provinces of Shanxi and Shaanxi and the autonomous region of Inner Mongolia together account for almost 70 percent of China’s proven reserves and more than half of national production (China Coal Resources 2014, NBS 2013). On the other hand, major coal-consuming centers lie in the eastern and southern coastal regions. The average distance coal is transported has been increasing, due to continued expansion of coal production in the west—with a more than three-fold increase in production in Xinjiang from 2007 to 2013 (CEIC 2014)—and the increasing dispersion of coal consumption locations in the east.

Despite the increasing distances, a more than four-fold rise in coal production from 2000 to 2013, and a 2.2 times increase in general freight turnover, the overall length of track increased by only 50 percent (CEIC 2014, NBS various years). Centralized government management together with lead times needed for investing in transportation projects in general and in railways in particular contributed to
time lags in responding to the increased transportation requirements of the coal sector.

These disparities made transportation the crucial factor in the development of the Chinese coal industry (Tu 2011). The costs of railway bottlenecks, in particular, were a key driver for delivered coal prices in coastal China (IHS 2013). Besides increased costs, logistical problems affected the overall stability of the coal market in China by amplifying price volatility and causing defaults on contract obligations. Besides that, they also caused power outages and greater congestion for other types of freight.

The spot price of steam coal at Qinhuangdao, the major coal port terminal that connects inland coal production bases to eastern and southern coastal demand centers, provides an illustration of the costs of congestion. The average FOBT (Free On Board Trimmed) coal price, excluding VAT, in 2011 for the 5,500 kcal/kg specification was RMB 696 per ton (China Coal Resource 2014), whereas, according to our estimates, the average domestic production and transportation costs in China were only 240 RMB/t and 140 RMB/t respectively. This differential between price and average cost can be explained by congestion costs that drove marginal costs up and created room for arbitrage between consuming domestic coal and importing coal from abroad. In response to this situation, China has now completed several new rail lines devoted to moving coal that have relieved the congestion.

The problem of transportation bottlenecks in the Chinese coal market has captured the attention of academics and industry analysts. Since the mid 1990s, a number of studies have been dedicated to this issue. Appendix 1 discusses our approach in the context of the existing literature.
To explore questions related to congestion in the Chinese coal supply chain, we have developed a production and multi modal trans-shipment model of China’s domestic coal market, calibrated to 2011 data. The model aggregates coal supply by mining regions, includes coal transportation by rail, sea, inland waterways and trucking, and measures demand by province. The model finds the competitive equilibrium, which minimizes annual supply and transportation costs for meeting demand in 2011, incorporating both domestic and international supply. The modeling approach we use accounts for varying production conditions, dispersed demands and the flexibility of the logistical network by linking transportation nodes.

In this paper we address three questions related to congestion in the Chinese coal supply chain:

- What were the costs of the bottlenecks in 2011?
- How does relieving the bottlenecks affect regional prices and the international coal market?
- To what extent is China over-investing (or pre-investing) in railroad capacity, if at all?

We do this through modeling multiple scenarios in the coal module of the KAPSARC Energy Model of China (KEM-China).

The Coal Market in China

Domestic Coal Production

According to China’s Ministry of Land and Resources, total coal reserves in China amount to 1.42 trillion tons (Ministry of Land and Resources 2013). At current production rates of around 4 billion tons per year, China has centuries of coal resources.

However, the structure of coal resources and their geographical distribution implies that mining costs will increase as currently mined reserves deplete. Several traditional coal-producing provinces in the eastern and northeastern regions are depleting, resulting in higher production costs (Li and Tong 2008). As much as 53 percent of China’s total reserves are located 1000 meters or more below the surface (Xie et al. 2013), making extraction costly and technologically intensive. Low rank bituminous coal, with a range of heat content that spans the lower levels of bituminous and sub-bituminous, accounts for the majority (about 53 percent) of coal reserves, anthracite about 10 percent and coking coal just 4.3 percent (China Coal Resource 2014). Geographically, coal reserves in China are distributed unevenly: the ‘Coal Country’ provinces (Shanxi, Shaanxi, Ningxia and Inner Mongolia) contain about 45 percent of the estimated total (China Coal Resource 2014).

In general, the regions where production is increasing have long, flat supply curves. According to the IHS Coal Rush study, China’s average national production costs in 2011 fluctuated around 270 RMB/t, with the heat content adjusted to 5,000 kcal/kg (IHS CERA 2013). However, depending on mine location, these costs can differ by more than 20 percent, primarily due to varying geological characteristics and local fees. The fees tend to change in line with coal price trends, as local authorities try to balance fiscal objectives and maintain the competitiveness of their coal producers. Local fees can constitute more than 40 percent of total production costs, depending on local policies and mine ownership type (IHS CERA 2013).

Ownership also affects both the structure and total amount of a mining unit’s operating expenses. Large publicly owned companies, such as China Shenhua Energy Company Ltd., tend to be more efficient in their operations and more flexible in their human resource policies. According to Macquarie estimates, Shenhua’s costs are about half of those of a typical large State Owned Enterprise (SOE) in Shanxi province (Macquarie 2013). SOEs generally tend to be less flexible and to have higher costs related to their social responsibilities, while small Town-Village Enterprises (TVEs), in general, do not have streamlined business processes or modern equipment and cannot benefit from economies of scale.
Inefficient cost structures and coal price fluctuations undermine the stability of the market and have often led coal producers, both Small and Medium Enterprises (SMEs), and large companies, to breach the terms of their contracts (Credit Suisse 2012). Industry regulations further complicate the issue of compliance with contractual obligations. Officially, market pricing of coal was introduced in 2002 but since then the National Development and Reform Commission (NDRC) has tried to impose price caps on thermal coal on several occasions (Tu 2011). The NDRC has also imposed a long-term contract scheme with prices fixed for the duration through a centralized allocation of coal transportation capacity. This mechanism has distorted the market by restricting access to transportation for coal bought on internal spot markets as well as coal imports. As a result, in 2009, only about half of the coal contracted under long-term contracts was actually delivered to consumers (Economist 2011).

Coal Transportation

Depending on the location of coal production and consumption, industry participants can choose from several alternatives, based on tariffs and capacity constraints. China has four major modes of coal transportation: railways, trucks, inland water vessels and seagoing ships. The transmission of electricity generated by coal-fired plants along UHV lines and coal-to-liquids transformation can, to a certain extent, replace the physical movement of coal.

Railways are the dominant transportation mode for coal, with more than 60 percent of the product transported by rail via general and coal dedicated lines (IHS CERA 2013). Coal accounted for 52 percent of total national railway freight traffic in 2012 (NDRC 2013).

Large vertically integrated companies in the coal production sector tend to operate own railroads: in 2012 Shenhua reported 176.2 billion ton km (tkm) of movement on its own railway (Shenhua 2013). However, for the most part, railroads are owned, managed, and regulated by the state. Freight rates are divided into seven classes—with coal in class 4, implying that it has to compete with other types of cargo—and the structure of the railway freight mix can have an impact on transported coal volumes. Also, in many regions freight is competing with passenger traffic for railway capacity. However, new high speed passenger rail lines have now been built to reduce passenger congestion on mixed freight rail lines.

The structure of the railway tariff for coal includes, on top of the base rate for loading and unloading (13.8 RMB/t), a variable distance charge (0.0753 RMB/tkm), a construction fund surcharge for funding the expansion of rail capacity (0.033 RMB/tkm) and an electrification surcharge (0.012 RMB/tkm). The base rate and variable distance rate provide a reference for the operating costs of coal railway shipments. The construction surcharge is collected from customers, given to the government and then returned to the national freight company as a payment for investment.

For rail lines owned by private companies, rates can vary significantly, particularly for short haul shipments. For example, the RMB/tkm tariff for coal shipments to Datong from Zhunge’er, Inner Mongolia, is 0.12 RMB/tkm, which is more than double the rate (0.05 RMB/tkm) charged to reach the same destination from Guoleizhuang, Hebei (Standard Chartered 2012).

Roads are used extensively for transporting coal short distances because of the flexibility of trucking: from mines to railway loading facilities and from rail terminals or ports to consumers. When coal shipments can be used as backhauls for vehicles that move goods to the coal regions, trucking can be competitive with rail for longer distances, as against situations where the trucks are used only for hauling coal and return empty and coal bears the full cost of the round trip. Often, trucking is the only logistical option available for the local TVE mines. Despite these economic uses of trucking, the volume of
trucked coal provides a good proxy for estimating congestion volumes and costs for rail movements. Through the 2000s, the volume of long distance trucking increased substantially, which contributed to the rise in the cost of coal deliveries and increased the competitiveness of imported coal. About 20 percent of coal produced is transported by road (Tu 2011).

However, trucking is less energy efficient, more costly and less safe than railways. Highway transportation rates depend on oil prices and vary between 0.3 RMB/tkm and 0.8 RMB/tkm (Standard Chartered 2012)—on average several times higher than railway tariffs.

The throughput of coal transported by inland water routes remains relatively small compared with railways. 184 MMT of coal (about 5 percent of total coal output) were shipped from inland river terminals and 390 MMT arrived from all sources in 2011. Despite competitive freight rates of 0.07 RMB/tkm to 0.2 RMB/tkm (IHS CERA 2013) and congested land transport, the share of coal transported by river has not increased substantially, primarily due to geography: major inland water cargo routes are limited to the Yangtze River, the Pearl River, the Grand Canal and several minor rivers. Water routes mainly serve as segments in multi modal shipments connecting internal coastal, seaborne freight and imports with inland consumption locations, or inland production centers with consumers.

The main seaborne route for coal is from northern ports (Qinhuangdao and others) that trans-ship coal coming from the Coal Country and the northeastern region to eastern and southeastern ports. Affordable tariffs (on average 0.024 RMB/tkm) and congested railways have contributed to the steady growth of this mode over the last decade. In 2011, the transported coal volume reached 620 MMT (IHS CERA 2013), comprising about 22 percent of total freight handled in major coastal ports (NBS 2013). Expansion of ports is restricted by inland bottlenecks that limit the arrival of coal at major terminals.

Transportation bottlenecks have led to a surge in seaborne coal imports. The total volume of imported coal increased more than 30 times from 2003 to 2013 (NBS 2013), with Chinese seaborne coal purchases accounting for 25 percent of global maritime trade in coal in 2013 (Kendall 2013).

Other alternatives to coal transportation that are being explored include coal conversion and UHV grids connecting coal-producing regions with major energy demand centers. The 12th Five Year Plan for the Petrochemical and Chemical Industries envisages extensive coal-to-chemical capacity construction in the coal-producing provinces of Xinjiang, Gansu and Anhui. Analysts estimate that the potential capacity of these projects amounts to 604 MMT of coal (Standard Chartered 2012). China’s 12th Five Year Plan for Energy Development (NDRC 2013) proposes the construction of a comprehensive UHV power grid with the focus on “two approaches to transportation of energy: coal transportation and electricity transmission, gradually relying more on electricity transmission”.

However, these projects are characterized by high construction costs, technological complexity and lower coal-equivalent throughput capacity. Coal-equivalent throughput of 1.2 RMB/tkm compares with the RMB 0.4 average rail capex according to Standard Chartered (2012). This suggests that current UHV grid development projects will not have a substantial impact on coal volumes transported. Analysts estimate that, in the short term, no more than 7 MMT of coal equivalent will be sent via UHV lines. In the long run this figure can increase to the level of 43 MMT, meeting less than 4 percent of the total coal transportation requirements (IHS CERA 2013, Standard Chartered 2012).
The KEM-China Model

Structure of the Coal Module of the Model

KAPSARC has developed a production and multimodal trans-shipment model of China’s domestic coal market. It covers coal supply aggregated by mining regions; the shipment of coal by rail, sea, and inland waterways and truck from supply nodes to demand nodes; and coal demand by province. KEM-China is a partial equilibrium model that is a linear program that minimizes China’s coal supply and shipping costs in a one-year period, mimicking the supply and distribution patterns of a competitive coal market. These costs include all operating and annualized investment costs relating to domestic coal production, transportation, and imports.

The cost of shipping coal is measured per ton and the value of the coal depends on its heat content. Consequently, the model can represent tons moved consisting of different grades with different heat contents. If a region burns a low grade coal, it needs more transportation capacity to meet demand.

The model uses exogenous coal demand for each province, with 31 primary demand nodes located at the provincial capitals. Tibet is the only province or autonomous region with no exogenous demand for coal. Inner Mongolia is split into western and eastern demand nodes. Its reported provincial coal demand is disaggregated based on the GDP of the eastern and western regions of the province.

Coal production is separated into 36 coal mining regions. Each mining region includes one or more mining units, differentiated by privately owned enterprises, SOEs and TVEs. In addition, each unit is represented by the mining method used (open cut or subsurface), the coal type produced (thermal, lignite, hard coking coal and other metallurgical coal (see Appendix 3), the heat content for thermal coal, the production yields for primary and secondary washed steam and metallurgical coal and the associated mine gate costs.

All metallurgical coal is processed using an average primary washing yield for each mining unit. A by-product of washing, secondary washed coal, is assigned an average heat content and is treated as a source of thermal coal, with the volumes added to steam coal production data. For steam coal and lignite, the model optimizes the proportions of product washed at the mine and sent raw, based on the average yields of the primary and secondary product. Volumes of raw and washed thermal coal are then aggregated into one of nine bins that represent different heat contents, ranging from 3,000 to 7,000 kcal/kg with steps of ±250 kcal/kg. This aggregation is carried out to reduce the number of transportation variables.

Mine expansion is included in the model with fixed limits on the volume of additional coal extracted from each specific production unit in all mining regions, based on the Coal Rush study (IHS CERA, 2013).

Coal imports are included for steam and metallurgical coal sourced from the international seaborne market and by rail over major land borders. A single seaborne coal price is used for all imports supplied to domestic port nodes, with imports at available rail nodes based on the coal price from the neighboring source country (Mongolia or North Korea). Coal exports are represented by fixed volumes for different nodes based on the reported volumes by SXcoal (China Coal Resource 2014) for 2011.

In order to capture the effect of distances on transportation costs more accurately, the operation and maintenance costs of coal transportation by rail and waterways are broken down into fixed and variable components. For coal transportation we use arc-flow variables that track the flows between the nodes in the model’s transportation network. The trans-shipment arcs represent existing major rail corridors. The model restricts the construction of new corridors to rail segments that have been proposed by the government and industry.
In addition to the 36 coal mining regions and 31 primary provincial demand nodes, 20 additional intermediate transportation nodes are included that segment key rail and port transportation pathways. The coal supply and intermediate trans-shipment nodes consume a limited portion of the aggregate coal demand in a given province or region. As a disaggregation of coal demand by province is not known, maximum consumption outside the primary demand node is set to the provincial total divided by the number of nodes in the province. Rail transport is broken down into two types: coal dedicated and other mixed commodity lines. Capacity expansion is permitted for the former, while a fixed allocation and fixed capacities are used for coal transported on mixed commodity lines.

A mathematical formulation of the model is provided in Appendix 2.

Calibration

The model is calibrated to 2011 data. Appendix 3 contains a summary of the data coefficients and sources used for the calibration.

Exogenous demand for steam and metallurgical coal, as well as coal production capacities and mining characteristics for 2011 are obtained from the IHS Coal Rush study (IHS CERA 2013). For each mining unit IHS also provides estimates of primary and secondary coal washing yields.

Each mining unit is assigned a specific production capacity and relevant mine gate costs in the supply database of the Coal Rush study. Mine gate costs include all variable operation and maintenance costs, provincial and national resource taxes and mining area fees. However, the study does not include capital expansion costs. These are difficult to estimate because of mining conditions that are specific to each production unit, including variable seam width, depth of mines, and seam angles. In order to include mine expansion in our optimization model, which we investigate in one of our alternate scenarios, we use the coal production forecasts for 2015 from the IHS Coal Rush study to cap mine expansion as a proxy for where capacity can be expanded.

Calibrating the transportation model involves assigning coal capacities and transportation costs for each of the shipment modes besides trucking: rail, sea and river ports. A rail transportation network represents known linkages among the nodes. For major rail lines dedicated to coal, existing annual capacities are taken from the Standard Chartered report (Standard Chartered 2012). We use the Standard Chartered report, the NDRC’s 12th Five Year Plan and reports published by SXcoal (China Coal Resource 2014) to identify new rail links that have been proposed or are under construction. This information is then used in alternative scenarios to allow the model to build new as well as to expand existing railway capacities, unlike the Calibration Scenario which has current capacities fixed.

For mixed freight rail lines linking the majority of nodes outside the major coal-producing provinces, capacity allocated to coal is estimated from interprovincial flows reported by the China Transportation Association (Berkeley Lab 2013). We include unlimited trucking capacity on each link in the trans-shipment network.

The constraints on the 28 sea and river links and port nodes are represented differently than the capacity constraints on rail links; they are capped by the annual port turnover, not by the waterway throughput capacity. The model does not constrain the amount of coal that can be transported along inland waterways with exogenous factors, such as hydro dams and bridge projects. The 20 river links are connected to major sea ports located at the mouths of rivers, e.g. the ports of Shanghai and Nanjing on the Yangtze River Delta. Major coal port capacities have been sourced from the Standard Chartered report (Standard Chartered 2012) where available.
Coal export volumes are fixed at major export nodes. These volumes are taken from the export quantities reported by SXcoal for 2011. Export prices are set to the marginal cost of coal supplied to the export node, as determined by the model. We include 2011 exports in the model calibration to assess the impact they have on the constrained inland transportation system.

By running the model without allowing investment in new rail lines or mines, we obtain the Calibration Scenario, which replicates what actually happened in 2011.

In the Calibration Scenario, the costs for shipping on the coal dedicated railway lines are the published tariffs paid by the users, not the actual costs of running the railroads. Using the 2011 tariff structures for coal amounts to optimizing the flows on the existing coal dedicated railway lines from the users’ perspective. As explained earlier, the tariff consists of a freight-handling rate, a distance based rate, an electrification surcharge and a construction fund surcharge. Using the actual prices paid by consumers better replicates the reality of China’s coal production and transportation sector in 2011.

Figure 2 provides a representation of the major supply, demand and transportation nodes of the model. The volumes produced and demanded in 2011 are indicated by the sizes of the circle symbols.

The major deviations between the calibration run and what actually occurred in 2011 are as follows:

- The total output of domestically produced coal under the Calibration Scenario is 113 MMt lower than estimated by IHS CERA. This gap can be partially explained by higher imports of thermal coal driven by inland transportation congestion.
costs: 197 MMt (5,500 kcal/kg) in the model as against 138 MMt (weight) of coal imported in 2011. However, in reality, heavy regulation of coal imports distorts the optimal supply allocation. Another factor that may affect lower total domestic production of raw coal is the model’s preference for those coals with higher heat content.

- The total amount of coal transported by rail (2.2 billion tons) matches the IHS CERA estimates of 2.3 billion tons, suggesting that coal railway capacity was fully utilized. Sea freight of coal exceeds 2011 actual data due to higher seaborne imports.

**Assessing the 2011 Coal Supply Chain Capacity**

**Scenario Design**

We use the KEM-China model to illustrate the potential economic gain that could have been generated in 2011 if one had been able to revisit 2011 and add new infrastructure to existing facilities.

We develop two counterfactual scenarios and compare them with the Calibration Scenario with 2011 capacities. First, we estimate the effects of optimizing only the coal logistics system by allowing the model to invest in new transportation infrastructure but not mine expansion (Investment in Transportation Scenario). Second, we allow the model to invest in both production expansion and transportation infrastructure (Investment in Production and Transportation Scenario).

As explained in the text box below, the two counterfactual scenarios minimize the sum of all annual economic costs incurred—annualized capital costs plus operating costs—instead of accounting costs. For each scenario, we assess the total annualized economic costs, the marginal costs of the coal delivered at demand nodes, the imports and the share of trucking in total coal freight. In the Calibration Scenario, the total economic cost is determined ex-post as the amount of operating expenses. Table 1 presents a comparison of the model outputs for all scenarios.

<table>
<thead>
<tr>
<th></th>
<th>Calibration</th>
<th>Investment in Transportation</th>
<th>Investment in Production and Transportation</th>
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<tr>
<td><strong>Annual Economic Cost, billion RMB</strong></td>
<td>1,511</td>
<td>1,405</td>
<td>1,283</td>
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<td><strong>Cost Savings, billion RMB</strong></td>
<td>-</td>
<td>107</td>
<td>228</td>
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<tr>
<td><strong>Investment in Transportation, billion RMB</strong></td>
<td>-</td>
<td>152</td>
<td>228</td>
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<tr>
<td><strong>Share of Trucking in Total Coal Transportation:</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Per ton</td>
<td>20 percent</td>
<td>4 percent</td>
<td>2 percent</td>
</tr>
<tr>
<td>Per ton/km</td>
<td>8 percent</td>
<td>1 percent</td>
<td>0.5 percent</td>
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<td><strong>Demand-Weighted Average Marginal Cost of Thermal Coal (5,500 kcal/kg), RMB per ton</strong></td>
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<td>729</td>
<td>457</td>
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<td><strong>Demand-Weighted Average Marginal Cost of Metallurgical Coal, RMB per ton</strong></td>
<td>1,339</td>
<td>1,371</td>
<td>899</td>
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<td><strong>Thermal Coal Supply:</strong></td>
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<tr>
<td>Domestic, million tons (5,500 kcal/kg)</td>
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<td>2,602</td>
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<td>Imports, million tons (5,500 kcal/kg)</td>
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<td><strong>Metallurgical Coal Supply:</strong></td>
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<td>Domestic, million tons</td>
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<tr>
<td>Imports, million tons</td>
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<td>45</td>
<td>25</td>
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Table 1 – Model’s Results for the Three Scenarios, 2011
Debottlenecking Coal Supply: Cost Savings and Effect on the International Market

In the first counterfactual scenario (Investment in Transportation), we do not include domestic mine expansion but we do include the expansion of rail and port capacity. Through reduced transportation congestion, the model produces an annual saving of RMB 107 billion, compared with the Calibration Scenario—slightly less than half of the potential gains achieved by simultaneously optimizing production and transportation.

The improved inter-provincial and inter-regional connectivity leads to a leveling of mine gate prices across the provinces and increased domestic production from existing capacity that reduces imports by 43 percent. Because coal production is not expanded, the coastal provinces still have to rely on relatively expensive imports. Prices decrease only marginally in the coastal provinces because imports set the price; the biggest drop of 7.2 percent occurs in Shandong. The model arbitrages between selling locally the last ton produced and transporting it to a demand node where it can substitute for an imported ton. As a result, the marginal cost of coal delivered inland reflects the import price minus the transportation costs from that inland node to the coast, unlike the Calibration Scenario where inland mines can sell incremental production only locally. Removing transportation bottlenecks ends the locational advantages of inland consumers, most obviously in inland coal-producing provinces, such as Inner Mongolia, Ningxia and Xinjiang. In these regions, the marginal costs of locally delivered coal increase by 29–42 percent.

Another way to describe this phenomenon is that building transportation infrastructure which allows a commodity to expand its market to more regions, while production capacity remains fixed, increases prices near the supply areas. As an aside, this phenomenon explains the opposition of some gas-consuming manufacturers to LNG projects in Australia and the U.S.

In this scenario, too, the constraint on domestic production creates for the local producers resource rents which have a profitability exceeding a market rate of return on investment. The total amount of rent is slightly higher than in the Calibration Scenario because the total cost of delivering coal is lower due to the debottlenecking. Yet the marginal values (producers’ prices) of the coal are higher, because any additional production would substitute

Railway Tariff Structure, Economic Costs and Scenario Design

The tariff represents the price paid by users. Using the 2011 tariff structure in the Calibration Scenario amounts to optimizing the use, from the users’ perspective, of the existing coal dedicated railway lines. It is therefore appropriate in order to replicate the reality of China’s coal transportation sector in 2011.

Using the tariff structure in the counterfactual scenarios would, however, be problematic. The surcharge applied to an existing line is akin to a sunk investment cost, and is therefore an accounting cost. Since the surcharges are applied equally to new and existing lines, they lower the tariffs costs/rates for new lines, resulting in users abandoning existing rail capacity and a potential over-investment in new rail capacity.

To compute the congestion costs incurred in 2011, we need to construct a counterfactual scenario that minimizes the total annual cost from an economic perspective, i.e., that does not include the sunk costs that are contained in accounting costs. For this reason, the counterfactual scenarios minimize a total economic cost consisting of the annualized investment costs (for new lines only) and the operating expenses represented by the freight handling costs and variable distance rates (for both existing and new lines).
for expensive imports. With higher prices and lower shipping costs, the profits (economic rents) for suppliers are higher. Thus suppliers increase their economic rents because consumers pay more.

In the second alternative scenario (Investment in Production and Transportation), when both production and transportation infrastructure are allowed to expand, the total cost savings amount to RMB 228 billion. Prices fall, with a significant decline in the marginal costs of both thermal and metallurgical coal. The resulting lower marginal costs of delivered steam coal make imported coal uncompetitive at the 2011 price, even in the southern coastal provinces. That is, the increased supply of steam coal removes the links between import prices and domestic supply prices, lowering domestic prices and shifting economic rents to consumers. This impact on rents illustrates the value of adopting an overall systems view of the supply chain, and not focusing on only one piece of a market.

We have not calculated the extent of the changes in the rents because government regulations and other features of the market can change who gets how much rent in ways we are not in a position to measure. For example, in the standard competitive market, congestion would lead to rents accruing to the transportation firms. On a congested rail link, this means the railway operator would charge more. Yet rail rates are regulated for common carriers and the customer costs of coal delivered this way are below the costs of delivering by truck. When the rail lines are owned by the coal companies, the coal companies get the rent.

Figure 3 illustrates the pattern of regional marginal costs in each of the three scenarios considered. The lower marginal costs from reducing bottlenecks are illustrated by the change from darker colors (higher marginal costs) on the left to lighter colors (lower marginal costs) on the right.

### Infrastructure Built and its Impact on Logistical Flows

In the Investment in Production and Transportation Scenario the model upgraded and built 4,765 km of new coal dedicated rail lines and added 130 MMt/yr of extra coal throughput at China’s sea and river ports.

Major mine expansions, shown in green in Figure 4, take place in coal regions with low production costs and significant reserves. Increased annual

![Figure 3 – Regional Marginal Costs of Steam Coal Delivered, RMB per ton, 2011](image)
output, measured in millions of tons, is: 307 in Inner Mongolia, 119 in Shanxi and 106 in Shaanxi, giving total domestic production of 3,630 MMt for all of China. On the other hand, production in less competitive provinces, such as Shandong and Guizhou, is reduced. Seaborne imports and anthracite supplied from North Korea drop to zero. Metallurgical coal imports from Mongolia, 25 MMt, remain competitive due to low production costs relative to other sources of metallurgical coal.

Optimization of the coal supply chain also results in the redistribution of coal flows by mode of transport. The major shifts occur within the railway and trucking segments. In the second counterfactual analysis, significant investments and increased flows raise the share of coal transported by rail from 64 percent to 76 percent. The percentage trucked, on the other hand, drops from 20 percent to just 2 percent due to the reduction in rail bottlenecks. The rail investments result in the full elimination of coal trucking from major supply nodes in the north and west, reducing trucking flows to the central provinces, where no new railway capacity is built.

Figure 5 shows the construction of new rail segments and ports in the Investment in the Production and Transportation Scenario. The expansion of rail lines (orange lines) and ports (blue dots) is optimized using the economically efficient rail transportation cost (tariff excluding surcharges) and total annualized capital costs of each new rail segment.

**Investment and Profitability of Railway Projects**

Our Investment in Production and Transportation Scenario requires the building of 4,765 km of new lines, while Standard Chartered (2012) lists projects totaling 7,751 km of new lines. In our scenario, the associated total investment cost amounts to RMB 215 billion. Standard Chartered reports a cost estimate of RMB 511 billion, which excludes the cost of projects for which they have no estimates. Extrapolating from the lines for which they have expansion costs, we estimate the total cost of all projects in their report to be RMB 579 billion, more than double the amount in our scenario.
Economic Impacts of Debottlenecking Congestion in the Chinese Coal Supply Chain

Figure 4 – Change in Total Coal Output at Supply Nodes, Investment in Production and Transportation Scenario, 2011

Figure 5 – Transportation Capacity Expansion, Investment in Production and Transportation Scenario, 2011
Does the Existing Tariff Structure Retain the Efficiency of Marginal Cost Pricing?

All the components of a rail freight tariff are set by the Chinese government. While the base rates for freight handling and transportation distance have been updated on a regular basis, the electrification and construction surcharges have remained unchanged. This regulatory framework makes it difficult to adjust tariffs in order to adequately represent changes in transportation costs. Could this result in significant economic inefficiencies?

We implemented an alternative Investment in Production and Transportation Scenario with the tariffs paid by the users of dedicated coal railway lines, as in the calibration case, and optimizing the coal supply chain from the users’ perspective. The total economic cost in this case is RMB 1,288 billion, i.e. only 0.4 percent more than in the counterfactual scenario where economic costs are minimized. The average marginal costs of delivered thermal and metallurgical coal are also very similar. This suggests that the existing tariff structure does not incur significant economic costs. However, using this alternative approach shows additional railway investments of RMB 81 billion, compared with the Investment in Production and Transportation Scenario, which uses economic costs.

As an additional reference point, we have estimated the total investment costs of coal railway projects reported in China since 2011 through 2014, based on the capital costs used to calibrate the model. Sections of these projects appear in the Investment in Production and Transportation Scenario and have been labeled in Figure 5. They include the 200 MMT/yr Zhangtang railway linking the Ordos basin in Inner Mongolia to the Caofeidian port in Hebei (Wang 2013), the 200 MMT/yr Shanxi central-south coal railway connecting the mining units of Southern Shanxi to the Rizhao port in Shandong (Wang 2013), the 200 MMT/yr Menghua coal railway linking Inner Mongolia, Shaanxi, Shanxi, Henan, Hubei, Hunan and Jiangxi provinces (Yang 2014), investments by the Shenhua coal group connecting Western Inner Mongolian coal to northern Shanxi (Hao 2014), the 60 MMT/yr Hongzhuo line built in Xinjiang and a 100 MMT/yr expansion of the Jincheng line connecting Eastern Inner Mongolia to ports in Liaoning (Cornot-Gandolphe 2014). This gives a total railway investment cost of RMB 375 billion for the projects actually built since 2011.

This raises the following question: for 2011, what is the economic cost of these larger investment plans compared with our counterfactual scenario? To address this, we examine two additional scenarios in the model. In the first additional scenario, the model includes the construction of all rail expansions reported since 2011. The resulting annual cost saving over the Calibration Scenario (including the cost of the imposed expansion) is RMB 217 billion, i.e. RMB 11 billion less than in the Investment in Production and Transportation Scenario. This decrease in cost savings is equivalent to the annualized value of the incremental investment cost (RMB 160 billion). Since the reduction in economic gain is roughly the increased capital expenditure, the operating benefits of using the additional railway lines are negligible.

In the second additional scenario, the model includes the construction of all rail expansion projects considered by Standard Chartered. The resulting annual cost saving is RMB 28 billion lower than in the Investment in Production and Transportation Scenario. Surprisingly enough, this decrease in the cost savings exceeds the annualized cost of the imposed incremental investment. The reason is that some of the lines built by the model in our Investment in Production and Transportation Scenario do not appear when the Standard Chartered lines are required to be built, as they are not economic given this added capacity. Although the lines that are not built would generate significant
operational benefits, these benefits are not enough to repay their capital costs once all of the Standard-Chartered lines are built.

We now evaluate the economic value of three of the rail links for projects actually built since 2011, illustrating how the profitable links can be distinguished from the unprofitable investments. When examining an investment opportunity, decision makers often consider its internal rate of return (IRR) as an important economic criterion. The IRR is the value of the discount rate that makes the project’s net present value equal to zero. Calculating a standalone project’s IRR is generally straightforward. When simultaneous projects mutually influence each other’s net cash flows, as is the case for a transportation network, this is a much more difficult task since it requires making assumptions about other projects that would also be undertaken and the resulting cash flows. We use a simplified approach here that provides one view of the returns. To understand the complications that can provide different returns, see Murphy and Rosenthal (2006). The main complications are that the total benefits of all of the projects implemented as a package do not necessarily add up to the sum of the benefits over all projects when each is the only project implemented. That is, the benefits of a single project vary depending on where the project is placed in a sequential ordering of the projects.

Consider the additional scenario where the railway infrastructure is fixed to the levels actually built since 2011. To calculate the IRR of a selected segment of these rail projects, we measure the benefit of adding a small amount of capacity to a segment and calculate the internal rate of return for that small increment. The methodology is detailed in Appendix 4. Using the model’s marginal cost on the capacity constraint, we calculate the IRR of an additional unit of capacity for three segments of rail built since 2011:

- The northern segment of the Shanxi central-south corridor connecting the Ordos mining region of Inner Mongolia to Shaanxi and Shanxi has an IRR of 41.5 percent.
- A western segment, a project linking the Ordos region with the Zhangtang line in Hebei has an IRR of 27.5 percent.
- A northern segment of the Menghua Central China corridor connecting central Shaanxi to Shanxi and Henan has an IRR of -1.8 percent. That is, the sum of operational benefits is lower than the investment cost.

In our long-run Investment in Production and Transportation Scenario the capacities built along the Menghua line (Figure 5) were significantly lower than the actual levels built since 2011, suggesting that the actual capacities are oversized. This result shows how a systems approach can help avoid large negative returns on large infrastructure investments. It also supports the more general view that China’s ability to generate far reaching positive gains with massive infrastructure investments, as it did during the years of very high growth, may be on the decline.

Investments made since 2011 and those forecast by Standard Chartered, however, account for future coal demand growth projections that are not considered in this analysis. The static long-run scenarios estimate only the investments needed to resolve the 2011 bottleneck. Other factors that influence investment decisions should also be considered in future analyses. These include the reallocation of coal from mixed freight lines onto new coal dedicated lines, changes in import prices and variable project lifetimes depending on local mining conditions. A deeper investigation of this issue would require a multi period version of the model that incorporates future demand growth and global coal price projections into the investment planning.

**Conclusions and Implications for Further Research**

The model’s results indicate that significant economic gains in the Chinese coal industry were possible in 2011 through selected investments in
increased mine and transportation capacity, given the then existing capacity. Eliminating transportation bottlenecks, primarily in the railway sector, eliminates congestion costs. Investment in coal logistics also creates potential for expanding domestic coal production, which leads to additional economic gains. We observed synergies that illustrate the benefits of taking the systems view when investing in infrastructure for large and complex energy sectors.

During the period covered by China’s 12th Five Year Plan, the combination of a slowdown in coal demand growth and substantial investment in both passenger and freight rail capacity has relaxed the logistics bottlenecks restricting coal transport. This work provides a benchmark to compare the actual investment in resolving the logistical bottlenecks in recent years with what was needed.

A major structural difference between the calibration and investment scenarios is the definition of the railway costs, with or without rail surcharges. Excluding the surcharges in the investment scenarios results in significantly lower railway investments by removing the discounting of new lines versus existing lines. However, the economically efficient railway cost structure (without surcharges) generates only slightly higher economic gains and similar marginal costs of delivered coal, suggesting that this tariff structure is not creating major market distortions.

The model’s major capacity expansion routes are, to a large extent, in line with analysts’ forecasts, e.g. as presented in the Standard Chartered report, and actual projects being implemented in China. On the other hand, the investment amounts generated by the model are substantially below analysts’ estimates. This is in part due to the model’s investing in specific railway links between nodes rather than in entire transportation paths that connect supply and demand locations. Extending the model to multiple periods would help address the impact of future demand growth on long-term investment decisions, using the detailed representation of the transshipment network.

The model’s results indicate that a portion of the capacity expansion that has been undertaken is uneconomic. We use an approach that assesses the ‘systemic’ internal rates of return for three major coal dedicated railway lines built by the model and launched by the Chinese authorities since 2011. The estimated returns in two of them—41.5 percent and 27.5 percent—are high, because these railway lines contribute to eliminating high congestion costs by pushing out expensive 2011 coal imports. However, increasing the expansion of the northern sections on the third line results in the IRR’s declining to -1.8 percent, indicating overbuilding.

The ability to determine specific railway links and logistical nodes that require expansion was made possible by the detailed structure of our model. We found that in the case of China’s coal industry, a disaggregated representation is essential due to widely varying production conditions and demand that is dispersed throughout the country. Our model covers the coal supply chain comprehensively by encompassing major mining units, provincial level demand and four modes of coal transportation with intermediate logistics nodes.

Our next step in understanding energy in China is to include the electric power sector to represent the majority of China’s steam coal demand and electricity generation choices. This will allow an assessment of the expansion of the plant mix, the addition of China’s UHV grids and the expansion of the inter-regional transmission capacity.
Appendix 1: The Literature on Coal Logistics in China

Because bottlenecks in logistics systems affect corporate profitability, financial companies have studied China’s logistics issues to understand their impact on company and industry profits. Credit Suisse (2013), Morgan Stanley (2010) and UBS Investment Research (2013) have issued reports that focused on the rail transportation of coal, while Macquarie Equities Research (2013) and JP Morgan (2011) examined this issue within the general framework of China’s coal market.

The State Planning Commission of China, in collaboration with the World Bank, developed a decision support system to analyze coal transportation and efficiency of potential investments (World Bank 1994). Utilizing this tool, Kuby et al. (1995) constructed various scenarios for the coal industry, exploring the impact of transportation constraints on the country’s GDP. This project was ground-breaking in that it showed the Chinese authorities how to develop national plans for infrastructure while using market mechanisms for providing products.

Todd and Jin (1997) identified railway congestion as the main logistical issue for the coal sector, showing how long congestion has been a problem. Zhao and Yu (2007) proposed improving railway and road coal transportation, extensive development of the sea and river routes and focusing on pipelines as an alternative in the long run. Cheng et al. (2008) applied statistical and spatial analysis to re-examine the drivers of interprovincial coal flow and articulated the importance of regional price differentials of coal. Other models of China’s coal logistics have provided a detailed analysis of coal transportation options. Xu and Cheng (2009) simulated inter-provincial flows of industrial coal, focusing on Shanxi, Shandong and Liaoning provinces. Zhang et al. (2011) applied an optimization model to minimize coal transportation costs on railways. Their work has the potential to be extended to examine the interdependencies with other freight modes such as sea/river freight and road transportation. Mou and Li (2011) developed a coal logistics optimization model focused on rail and water transport modes. We extend this work by including all modes of transport, such as trucking, and by introducing a greater level of disaggregation to better highlight bottlenecks on segments of rail lines.

A number of modeling studies are devoted to coal-to-liquids technologies and electricity generation in the coal regions, combined with ultra-high voltage (UHV) transmission lines that can serve as alternatives to physical coal transportation. Huang et al. (2008) analyzed the coal-to-liquids technologies and applied a partial equilibrium model to assess their impact on coal markets under various scenarios. Models focusing on UHV grids primarily address the technological aspect of the projects (see Wang et al. 2014), while the analyses of UHV transmission within the context of coal transportation are generally of a qualitative nature (see Lantau Group 2013).

In addition, consulting and investment reports have been based upon proprietary models to assess the current and possible future states of the coal industry. The IHS CERA Coal Rush study (IHS 2013) provides an outlook for China’s coal sector based on a detailed analysis of coal supply, demand, and transportation. The China Coal Overview by HDR Salva (2014) covers railway coal transportation, derives coal cost curves in key demand centers, and addresses related policy issues. The Standard Chartered report (2012) applies a model to forecast the volumes of coal transportation utilizing a database of coal railways and production bases.

These studies provide assessments of China’s coal production and transportation sectors and present compelling modeling solutions to address specific industry issues. Still, an open-source, comprehensive model, which balances the necessary degree of disaggregation and data and computational costs, can provide a useful basis for discussions of the structure, efficiency, and effectiveness of the Chinese energy sector.
Appendix 2: Mathematical Formulation of the Model

The coal production and transportation system is a network with specific nodes and links. There are three types of nodes: supply nodes, demand nodes and logistics nodes which link rail, road and seaborne transportation routes. The links connect supply and demand nodes either directly or through logistics node(s). Import volumes are linked to port nodes. By solving an optimization problem, the model chooses transportation volumes and routes to minimize the total cost of production (1) imports and transportation, subject to the constraints (2)-(8). The model’s solution simulates the outcome of a competitive economy. The indices, exogenous parameters and variables used in these equations are as follows:

Indices

\( (i,j,k) \)  
index the nodes \( I \)

\( p \in I \)  
index of nodes that are ports for transfers between land and water

\( d \in D \subset I \)  
index of nodes that are provincial demand centers, nodes \( D \)

\( id(d) \)  
subset of demand nodes associated with \( d \)

\( i'd(d) \)  
subset of nodes \( i \) associated with demand center \( d \) but not including \( d \) \( \{i \in i(d) \mid i \neq d \} \)

\( q \)  
index of mining methods (surface and underground)

\( r \)  
index of coal washing state (raw, washed, and washed co product)

\( s \)  
index of coal production units for different producers (supply steps in the supply curve)

\( t, t' \)  
index of transportation modes (coal dedicated and mixed rail, river, sea, truck)

\( t(w) \)  
set of transportation modes on water (river, sea)

\( t(l) \)  
set of transportation modes on land (rail, truck)

\( u, uu \)  
indices of coal types (lignite, steam, hard coking, other metallurgical)

\( v \)  
index of bins for average calorific value

Variables

\( W_{t(l),t'(w),p} \)  
port capacity additions for land to water transfers

\( x_{t,u,v,i,j} \)  
trans-shipment arc flows from nodes \( i \) to \( j \)

\( z_{t(l),i,j} \)  
amount added to coal dedicated railway capacity connecting nodes \( i \) and \( j \)

\( I_{b,i} \)  
amount of coal loaded at port node \( p \)
\( y_{u,v,i} \)  
coal use at node \( i \)

\( s_{u,v,i} \)  
coal supply at node \( i \)

\( pr_{u,q,r,s,i} \)  
coal production at supply node \( i \)

\( imp_{u,v,f} \)  
coal imports at node \( i \)

Exogenous Parameters

\( Dem_{ud} \)  
demand for coal type \( u \) at node \( d \)

\( C_{t,i,j} \)  
anualized capital costs of new rail capacity per ton-kilometer between nodes \( i \) and \( j \)  
\((C_{t,i,j}=0 \text{ when } t \neq \text{rail})\)

\( C_p \)  
anualized capital costs per unit of new port capacity at node \( p \)

\( D_{i,j} \)  
distances connecting nodes \( i \) and \( j \)

\( OM_{t,i,f} \)  
fixed loading and unloading transportation cost

\( OM_{t,i,v} \)  
variable transportation cost

\( OM_{u,q,r,s,i}^{\text{coal}} \)  
unit cost of each production unit

\( P_{u,v,i} \)  
price of imported coal

\( CV_{u,q,r,s,i,v} \)  
table used to aggregate calorific value of production units into calorific-value bins

\( SCEv \)  
converts coal tonnage in bin \( v \) to a standard calorific value of 7000 kcal/kg

\( RW_{uu,u,r} \)  
share of washed metallurgical coal, \( uu \), that becomes steam coal \( u \)

\( Yield_{u,q,r,s,i} \)  
coal production yield

\( N_d \)  
number of demand nodes associated with provincial demand center \( d \)

\( Step_{u,q,r,s,i} \)  
limit on coal that can be mined on cost step \( s \)

\( ER_{t,i,j} \)  
existing coal dedicated railway capacities between nodes, \( tct(l) \)

\( AR_{t,i,j} \)  
existing mixed commodity railway capacities between nodes, \( tct(l) \)

\( EP_{t,p(i)} \)  
existing port capacity for transfers from land and water to the port, \( tct(w) \)

The objective function

\[
\text{Minimize} \quad \sum_{t,i,j} C_{t,i,j} D_{i,j} Z_{t,i,j} + \sum_{t \in (l), t' \in (w), p} C_p W_{t \in (l), t' \in (w), p} + \sum_{t,u,v,i,j} (OM_{t,i}^{\text{var}} D_{i,j} x_{t,u,v,i,j}) + \sum_{t,u,v,i} (OM_{t,i}^{fix} l_{t,u,v,i})
\]

rail capex  (1)

port capex

transportation opex
Economic Impacts of Debottlenecking Congestion in the Chinese Coal Supply Chain

\[
\begin{align*}
\sum_{t,u,v,i} (P_{u,v,i} \cdot imp_{u,v,i}) + \\
\sum_{u,q,r,s} (Yield_{u,q,r,s,i} \cdot OM_{u,q,r,s,i}^{coal} \cdot pr_{u,q,r,s,i})
\end{align*}
\]
coal import cost

coal production cost

The constraints in the model are the mass balance constraints of the transportation module:

**Production**

Coal supply

\[\sum_{u,q,r,s} Yield_{u,q,r,s,i} \cdot pr_{u,q,r,s,i} \cdot RW_{u,u,r} \cdot CV_{u,q,r,s,i,v} + imp_{u,v,i} \geq s_{u,v,i}\]  
(2)

Supply-curve steps

\[pr_{u,q,r,s,i} \leq Step_{u,q,r,s,i}\]

**Transportation**

Supply

\[\gamma_{u,v,i} + \sum_{t,j} x_{t,u,v,i,j} - \sum_{t,k} x_{t,u,v,k,i} \leq s_{u,v,i}\]  
(3)

Rail

\[\sum_{u,v} x_{t \in (l),u,v,i,j} \leq ER_{t \in (l),i,j} + z_{t \in (l),i,j}\]  
(4)

Ports

\[\sum_{u,v,j} x_{t \in (w),u,v,i,p,j} + \sum_{u,v,k} x_{t \in (w),u,v,k,i,p} \leq EP_{t \in (w),i,p} + \omega_{t \in (w),i,p}\]  
(5)

Loading

\[\sum_{u,v,j} x_{t,u,v,i,j} - \sum_{u,v,k} x_{t,u,v,k,i} \leq l_{t,i}\]  
(6)

Demand

\[\sum_{v,d} SCE_v(\gamma_{u,v,d}) \geq Dem_{u,d}\]  
(7)

\[\sum_{v,i \in i'(d)} SCE_v(\gamma_{u,v,i \in i'(d)}) \leq Dem_{u,d}/N_d\]  
(8)

The production constraint (2) covers domestic coal supply and imports. Coal production is tracked by mining method, production yield (raw, washed, and washed co product), and producer (represented as supply steps). Mined and processed thermal coal is aggregated in bins of similar calorific values. The transportation supply constraint (3) limits the flow of coal out of node i and local consumption \(\gamma_{u,v,i}\) to the available production at that node plus imports, \(s_{u,v,i}\). In (4) shipments from node i to node j are limited to the capacity of the rail corridor. Constraint (5) limits shipping out of port \(p(i)\) to the existing and new throughput capacity. Equation (6) determines the total amount of coal loaded at node i (\(l_i\)), excluding coal transiting through this node.

The demand constraint (7) ensures that the amount of coal type u used in nodes id(i,d) matches the exogenous provincial demand, \(Dem_{u,d}\), a standard coal equivalent energy content of 7,000 kcal/kg for thermal coal. Equation (8) limits the amount of coal that can be consumed outside the primary demand center, d, equal to the total demand divided by the number of demand nodes in the province or region associated with the provincial demand center. The calorific value of each unit of shipped coal is converted to the same energy content used to represent demand, with the coefficient \(SCE_v\). Metallurgical coal demand is an aggregate of hard coking and other metallurgical coals. This conversion is necessary because the capacity of coal lines is measured in tons, which approximates the physical volume, while consumer demand is measured in heat content.

The amount of coal transported by truck is unrestricted, which means capacity expansion variables are limited to rail lines and ports. Railway line expansion for coal is allowed in the model for existing and proposed major coal dedicated rail lines. Expansion of river and seaport capacity is permitted in the model for major inland waterways, such as the Yangtze River and the Grand Canal, and sea freight along China’s eastern seaboard.
Appendix 3: Data and Sources Used for Calibrating to Year 2011

Data Inputs

The coal transportation rates for rail are taken from the Credit Suisse report (Credit Suisse 2013). Railway tariffs, which include a railway construction fund surcharge of 0.033 RMB/tkm and railway electrification surcharge 0.012 RMB/tkm, are assumed to reflect the long-run marginal cost of rail transport. These represent the actual costs paid by consumers in 2011.

Sea transportation rates are based on average distance rates in the Standard Chartered report, 0.003 RMB/tkm, plus a 30 RMB/t loading and unloading cost. The same rate calculations are used for inland water transport. The average trucking rate applied for the model calibration is 0.55 RMB/tkm. Table A1 summarizes the coal transportation tariff structure.

<table>
<thead>
<tr>
<th>Transport Mode</th>
<th>Fixed Rate RMB/t</th>
<th>Variable Rate RMB/tkm</th>
<th>Surcharges RMB/tkm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail</td>
<td>13.8</td>
<td>0.078</td>
<td>0.045</td>
</tr>
<tr>
<td>Port (sea and river)</td>
<td>30</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Truck</td>
<td>-</td>
<td>0.55</td>
<td></td>
</tr>
</tbody>
</table>

Table A1 – Coal Transportation Tariffs by Mode

When running additional long-run scenarios on top of the calibration year, the expansion costs for existing and new dedicated railway lines are taken from Standard Chartered (2012). They vary by project, depending on existing infrastructure, local terrain and other factors. All capital costs have been discounted for a project lifetime of 30 years using a 4 percent rate, a standard rate used in the assessment of government infrastructure projects in China (Business Insider 2011).

A rate of 100 RMB/t was used to calculate the discounted capital cost of sea and river port expansion. This value is representative of the costs reported for three different port construction projects in China: Huizhou Hongxing Port (CRI 2013), Huanghua Port (Shanghai Shipping Exchange 2014) and Tangshan Port (China Coal Information 2013).

The average import prices (including Chinese port fees) set in the model at China’s southern, eastern, and northern ports are shown in Table A2. These prices are annual average ex-stock prices extracted from the SXcoal price database for major Chinese ports, after removing the value-added tax of 17 percent. We have also included imports sourced from two of China’s land neighbors in 2011. Coking coal imported from Mongolia is capped at 25 MMt, and anthracite imported from North Korea is capped at 10 MMt per annum.

<table>
<thead>
<tr>
<th>Source</th>
<th>Import Price RMB/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seaborne south (thermal 5,500 Kcal/kg)</td>
<td>773</td>
</tr>
<tr>
<td>North Korea (thermal 5,500 Kcal/kg)</td>
<td>607</td>
</tr>
<tr>
<td>Seaborne east (coking coal)</td>
<td>1,400</td>
</tr>
<tr>
<td>Mongolia (coking coal)</td>
<td>800</td>
</tr>
</tbody>
</table>

Table A2 – Coal Import Prices by Source Included in the Model Calibration, 2011
Key Data Sources

The data sources used for major model calibration inputs are represented in the Table A-3.

<table>
<thead>
<tr>
<th></th>
<th>Data Input</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Production capacity by mining unit and coal type</td>
<td>IHS Coal Rush 2013</td>
</tr>
<tr>
<td>2</td>
<td>Washed coal yields by mining unit</td>
<td>IHS Coal Rush 2013</td>
</tr>
<tr>
<td>3</td>
<td>Average calorific value of coal produced by mining unit</td>
<td>IHS Coal Rush 2013</td>
</tr>
<tr>
<td>4</td>
<td>Coal demand by type aggregated by province</td>
<td>IHS Coal Rush 2013</td>
</tr>
<tr>
<td>5</td>
<td>Coal imports price by type and source</td>
<td>China Coal Resource 2014/2015, China Statistical Yearbook 2013</td>
</tr>
<tr>
<td>6</td>
<td>Railway capacity</td>
<td>Standard Chartered 2012, Berkeley Lab 2013 (China Transportation Association)</td>
</tr>
<tr>
<td>7</td>
<td>Port (sea and river) capacity</td>
<td>Standard Chartered 2012, Yearbook of China on Transportation and Communications 2013, China Shipping Database 2014</td>
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<tr>
<td>8</td>
<td>Railway tariff</td>
<td>Credit Suisse 2013</td>
</tr>
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<td>9</td>
<td>Sea and river freight tariff</td>
<td>Standard Chartered 2012</td>
</tr>
<tr>
<td>10</td>
<td>Road transportation tariff</td>
<td>Standard Chartered 2012</td>
</tr>
<tr>
<td>11</td>
<td>Railway capital costs</td>
<td>Standard Chartered 2012, China Coal Resource 2014</td>
</tr>
<tr>
<td>12</td>
<td>Port capital costs</td>
<td>Standard Chartered 2012</td>
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</table>

Table A3 – Key Data Inputs and Sources Used for the Model Calibration, 2011
## Coal Demand, Supply and Reserves Data for 2011

<table>
<thead>
<tr>
<th>Province</th>
<th>Demand, Mmt IHS</th>
<th>Supply, Mmt IHS</th>
<th>Demand, Mmt CEGD</th>
<th>Supply, Mmt CEGD</th>
<th>Reserves, Mmt CEGD</th>
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<tbody>
<tr>
<td>Anhui</td>
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<td>145.2</td>
<td>140.8</td>
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<td>Beijing</td>
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<td>Chongqing</td>
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<td>71.9</td>
<td>43.6</td>
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<td>19.0</td>
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<td>Gansu</td>
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<td>47.4</td>
<td>184.4</td>
<td>2,350</td>
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<td>Guangdong</td>
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<td>9.1</td>
<td>63.0</td>
<td>20</td>
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<tr>
<td>Guangxi</td>
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<td>236.1</td>
<td>127.4</td>
<td>5,870</td>
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<td>180.1</td>
<td>9.5</td>
<td>6,180</td>
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<tr>
<td>Hainan</td>
<td>233.4</td>
<td>262.6</td>
<td>209.6</td>
<td>120</td>
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<tr>
<td>Hebei</td>
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<td>105.8</td>
<td>132.0</td>
<td>3,840</td>
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<tr>
<td>Heilongjiang</td>
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<td>158.1</td>
<td>5,180</td>
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<td>8.2</td>
<td>9,750</td>
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<td>11.3</td>
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<td>Hunan</td>
<td>94.8</td>
<td>69.2</td>
<td>130.1</td>
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<td>Jilin</td>
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<tr>
<td>Jiangsu</td>
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<td>21.0</td>
<td>1,080</td>
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<tr>
<td>Jiangxi</td>
<td>69.2</td>
<td>28.3</td>
<td>69.9</td>
<td>430</td>
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<tr>
<td>Liaoning</td>
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<td>56.0</td>
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<td>Inner Mongolia</td>
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<td>393.5</td>
<td>334.8</td>
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<tr>
<td>Shandong</td>
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<td>7,410</td>
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<tr>
<td>Shanghai</td>
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<td>61.4</td>
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<td>83,460</td>
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</tr>
<tr>
<td>Shanxi</td>
<td>92.9</td>
<td>856.0</td>
<td>114.5</td>
<td>93.8</td>
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</tr>
<tr>
<td>Sichuan</td>
<td>112.3</td>
<td>121.7</td>
<td>142.0</td>
<td>5,180</td>
<td></td>
</tr>
<tr>
<td>Tianjin</td>
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<td>52.6</td>
<td>411.4</td>
<td>300</td>
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<tr>
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<td>97.1</td>
<td>119.9</td>
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<tr>
<td>Yunnan</td>
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<td>96.6</td>
<td>5,970</td>
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<tr>
<td>Zhejiang</td>
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<td>147.8</td>
<td>0.2</td>
<td>40</td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3653.6</strong></td>
<td><strong>3761.9</strong></td>
<td><strong>4283.6</strong></td>
<td><strong>3953.1</strong></td>
<td><strong>215,800</strong></td>
</tr>
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</table>
Coal Type Definitions

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Steam coal</td>
<td>As per Chinese definition, all coal types can be used for steam.</td>
</tr>
<tr>
<td>Lignite</td>
<td>Thermal coal with NAR of less than 4,000 kcal/kg.</td>
</tr>
<tr>
<td>Hard Coking</td>
<td>Coking and fat coal.</td>
</tr>
<tr>
<td>Metallurgical</td>
<td>Other metallurgical coal except hard coking coal (including meager, meager lean, lean, one-third coking and gas) that is washed for coke making; as well as anthracite for PCI.</td>
</tr>
</tbody>
</table>

Appendix 4: Calculating the IRR for an Unbuilt Rail Link

If the build activity for a rail link is fixed and the associated capacity constraint is binding in the model, the internal rate of return (IRR) for that link can be calculated using the marginal value of the capacity constraint. The IRR of this rail link is equal to the value of the discount rate that sets the annualized total cost of the infrastructure equal to the marginal cost of an incremental unit of capacity (equation A3.1)

\[ C = D \cdot \sum_{n=1}^{N} \frac{1}{(1+IRR)^n} \]  

A3.1

- **C**: per-unit capital cost of the rail link
- **D**: value of an incremental unit of capacity, or the dual variable associated with the capacity limit
- **IRR**: internal rate of return
- **N**: lifetime of the project in years
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About the Project

The KAPSARC Energy Model of China (KEM China) project began in 2014 to study energy and environmental issues in China, focusing initially on the coal supply industry. KEM China has been developed to understand China’s energy economy and fuel mix, how they are impacted by government intervention, as well as their interaction with global markets. It optimizes supply decisions, minimizing fuel and technology costs, while taking into account the effect of government regulation on prices and the environment.